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TECHNICAL NOTE NO. 3/TN/51

Consideration of the Mechanical Properties of Rocket Propellants in Relation to their Use in Large Rocket Motors: Part 2. Plastic and Highly Elastic Propellants

by

C.G. Lawson.

This report contains classified information of overseas origin.

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Reference: XR. 413/10.

1. SUMMARY.

E.R.D.E. Technical Note 1/TN/51 dealt with colloidal propellants; the present Note covers plastic and highly-elastic propellants. The discussion of various rocket motor requirements leads to an evaluation of the mechanical properties of the propellants needed to satisfy these requirements, and to an indication of the methods which should be used to test these mechanical properties. Examples are worked out for P.I.B. plastic propellant at 60°C., and soft rubber. Various highly-elastic propellant systems are discussed, and speculations are made on some of these.

2. CONCLUSIONS.

The following more or less opinionative conclusions relate only to plastic or highly-elastic propellant stuck to the rocket tubing. Where special charge shapes are not mentioned, figures relate to the use of the propellant in a 24-inch, central conduit, motor.

2.1 The compression of the propellant in the standard 'flow test' must not exceed 40 per cent. Present-day plastic propellants should also be tested occasionally in pure shear, using a range of stresses, and results compared with those of routine compression and flow tests.

2.2 The cohesive strength must exceed 0.4 p.s.i., multiplied by the stress-concentration factor appropriate to the particular motor design considered.

2.3 Precise calculation of stress-concentration factors seems unlikely to be possible. Tests with photo-elastic models, or similar techniques, must be used.

2.4 The maximum shear in the propellant on temperature cycling of a cigar-burning charge is about:

$$\theta = 0.001.\ l\ \Delta T/a \text{ radians}$$

Where l is the charge length
a the radius
and ΔT the temperature range in centigrade degrees.

If θ is 0.5, and the range is + 60°C. to -54°C. (140°F. to -65°F.), l/a must not exceed 4.

2.5 The 'crack value' of propellants must exceed about 40 per cent. There is need for a crack value test using rapid stressing of the propellant; the result of such a test must exceed about 20 per cent. The fatigue crack value given over a standard very small number of cycles (to be stated by the users) in the fatigue plastometer must exceed ± 20% deformation at 25°C., and, in the case of propellants for use down to -54°C., ± 5% at -40°C. All

/propellants

propellants should withstand, say, 1,000 cycles at ± 6% deformation at 25°C, corresponding to extreme day and night variations in temperature.

2.6 There is, at present, no indication of a need to improve the impact strength of plastic propellants.

2.7 The presence of air (dispersed or otherwise) in a charge, leads to very severe strains on firing.

2.8 The limiting charge size for boosted or gun-launched plastic propellant motors, with a propellant 'viscosity' of 10^7 poises at the upper service temperature limit, appears to be around 2 feet in diameter, but this could be increased by using a low loading density, specially designed endrings, etc.

2.9 The acceleration of a motor filled with a highly-elastic propellant must be limited. For a modulus of rigidity of 4×10^6 dynes/square cm. (soft rubber), the acceleration of a 24-inch motor must not exceed about 60 g. The size of a gun-launched rocket filled with highly-elastic propellant must be severely limited. Under the worst charge design conditions, a 3-inch motor filled with soft rubber should withstand at least 400 g.

2.10 The 'viscosity' of P.I.B. plastic propellants is limited to 10^7 poises at 60°C. (140°F.) by the machinery and processing temperatures now employed.

2.11 Non-transient pressure gradients down the gas conduit of a large rocket motor should not exceed some 10 p.s.i./inch, otherwise longitudinal flow of plastic propellant or deformation of highly-elastic propellants may become severe. For small rockets, gradients up to 50 p.s.i./inch might be tolerated.

2.12 The elastic modulus of rigidity and damping of plastic and elastic propellants should be measured for severe rapid loading conditions simulating igniter pressure peaks, etc., so that the deformation under such conditions can be assessed (see also 2.5 relating to crack value).

2.13 Effects due to rotation of rockets, especially off-axis, should be calculated before firings under such conditions are made.

2.14 Deformation of the propellant due to a steady 10 g sideways acceleration of a guided missile could be tolerated by plastic or elastic propellants in motors 2 feet in diameter. Transient accelerations could be much higher in the case of plastic propellants.

3. INTRODUCTION.

3.1 Scope.

E.R.D.E. Technical Note 1/TN/51 dealt with colloidal propellants, not bonded to the wall of the rocket tube. This second Note covers cases where the propellant is sufficiently elastic or plastic to be bonded to the tube. It is, in many respects, an elaboration of a Technical Memorandum by James and Runnicles (1).

3.2 Charge Design.

The following common charge designs are considered:

/(i)

(i) Cigar-burning, the charge completely filling the rocket tube, which is closed at one end. It is assumed that if such charges are large, they will normally be stored vertically, open end upwards,

(ii) Cone and cylinder charge,

(iii) Star-centred charge without endrings,

(iv) Star-centred charge with plane endrings, and

(v) Star-centred charge with conical endrings,

These are sketched in Fig.1.

3.3 Symbols.

The following symbols are used in this Note; C.G.S. units are employed unless otherwise stated:

p = Gas pressure.

a = Inside radius of rocket motor tube.

t = Wall thickness of tube, or time (as indicated in context).

r = Radius to any point in the propellant.

l = Length of tube filled with propellant.

V_1 = Volume of tube filled with propellant ($\pi a^2 l$).

$F(a)$ = Proportion of tube volume filled with propellant.

$F(r)$ = Proportion of volume of a cylinder (concentric with the motor tube) of radius r which is filled with propellant.

V_2 = Volume of propellant ($V_1 . F(a)$).

ρ = Density of propellant.

η = 'Viscosity' of propellant above the yield point (plasto-viscosity).

n = Modulus of rigidity of propellant.

f = Acceleration of motor.

u = Final velocity of motor (in level flight at 'all burnt').

$v(r)$ = Rate of movement of propellant relative to motor tube ($d\,s\,(r)/dt$).

$s(r)$ = Extent of movement of propellant relative to motor tube.

T, T_1, T_2 = Temperature.

ΔT = Temperature difference.

/3.4

3.4 Mechanical Failure.

The charge is considered to have failed mechanically when it has deformed to an unacceptable degree, or has cracked either at the wall or internally. The degree of overall deformation which is acceptable is a function of charge size, shape, free space in the gas conduit and rocket tube, etc., but has been taken as being equivalent to a maximum angle of shear over a large region of about $\frac{1}{2}$ radian or less, and corresponding to a figure of 25 per cent. in the compression test, in which a cylinder of propellant is loaded longitudinally and its deformation is divided by one-hundredth of the original height. Local deformations considerably in excess of this figure may, however, be encountered at lines of stress concentration in the charge, without unacceptably large overall deformations.

4. ROCKET MOTOR REQUIREMENTS.

4.1 Requirements for Continuous Storage at One Temperature.

On continuous storage at a constant temperature, the weight of the propellant causes a steady stress in one direction. This stress must not cause an unacceptable deformation, even when any effect of vibration or jolting caused by transport is superimposed on it. Therefore the 'yield point' (corresponding to the highest acceptable deformation of half a radian) must be well in excess of this stress, and the crack value must exceed the deformation at any lines of stress concentration.

For a charge of Type (i) (Section 3.2), the stress is a hydrostatic pressure, which will only rupture a solid if the latter contains voids, assumed to be obviated by inspection after manufacture.

Charge Types (ii) and (iii) usually have a 'density of loading' varying from 60 to 90 per cent. Taking the higher figure, the average shear stress at the wall on vertical storage is:-

$$0.9 \pi a^2 l \rho g / 2 \pi a l = 0.45 \quad a g \rho$$

In the case of a 2 foot diameter charge of propellant, of density 1.8 gm/ml., this is 24,000 dynes/square cm. (about 0.4 p.s.i.).

Therefore the 'modulus of rigidity' of the propellant (corresponding to a maximum angle of shear of half a radian) must be at least 5×10^4 dynes/square cm. if it is to be used in a motor of this size. Correspondingly, in the compression test, the 'Young's modulus' must be at least 1.5×10^5 dynes/square cm., since Poisson's ratio may be taken as 0.50. That is, the equilibrium compression with an 850 gram weight must not exceed 77 per cent., starting with a cylinder 1.5 cm. in diameter. The 'flow-test', in which the stress is applied by a weight of 200 grams acting for 16 hours, similarly must not give a compression of more than 40 per cent. Neither of these tests is, however, strictly valid, since in the first place compression can be regarded as the sum of two perpendicular shears plus a hydrostatic pressure, and does not give the same conditions as one simple shear, while in the second place the 'modulus' calculated for plastic propellant is a function of the degree of strain hardening. It is very small indeed for small strains and very large for large strains. There is, therefore, a need for carrying out a set of 'flow tests' using several different stresses, so

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that for each propellant a family of curves could be obtained. This was done by Freeman (2) using a plastometer designed by A.G. Ward (3) which gave a simple shearing stress, covering the rate of shear as well as final 'equilibrium' deformations, but the method is far too tedious to be used as a routine test.

The stress involved in the 'flow test' (using 200 grams) corresponds to the shearing force at the wall of a motor about 40 inches in diameter, but it is found in practice that pellets of propellant can be squashed considerably without cracking, whereas in rocket motors plastic propellant may crack after some days of hot storage. This is due to several causes whose relative importance cannot be assessed. In the flow test there is a small hydrostatic component of stress, absent or even negative on the top surface of a stored charge. The cracking in a motor may also be due to 'ageing' of the propellant or to some discontinuity in the surface causing a stress-concentration. Even with apparently simple symmetrical models, such as lap joints, Mylonas (4) has shewn that stress-concentrations occur on the surface of an adhesive in a way quite unpredicted by elementary considerations such as those used in this Note.

The shearing stress generated in the propellant for charges of Types (ii) and (iii) degenerates at the bottom surface of the propellant into a compression, and at the top surface into a tension, with a maximum value of $0.45\ a\,g\rho$.

On horizontal storage of charge Types (ii) and (iii), a hydrostatic pressure is generated at the bottom of the charge which will somewhat diminish the shearing stress at the sides to a value below that for vertical storage. There is, however, a vertical tension in the top half of the filling, superimposed on a shearing stress, the latter falling to zero and the former rising to a maximum at the very top. The value of this maximum tensile stress is not more than $0.45\ a\,\rho\,g$ (0.4 p.s.i. for a 24 inch tube).

For charges with endrings, Types (iv) and (v), the general run of stress is very similar to that in charges without endrings, except in the neighbourhood of the endrings. Owing to the complicated nature of the problem no stress analysis has been made. On vertical storage there will be a tensile stress in the propellant at the top endring and a compression near the bottom endring. The weight of the charge will be supported partly by the endrings and partly by the vertical walls of the tube. Considering a point in the propellant very near to the top endring, and some distance from the wall of the motor, a small vertical displacement in the propellant will give rise to a relatively high tensile strain of the material between this point and the endring, compared with the amount of shear between the point and the motor wall. Hence the main part of the weight of the propellant near the endring is, in fact, taken by tensile stress, and only a small part by shear. If the endring is perpendicular to the axis, the tensile stress will clearly be greater than when a conical endring is used, for the latter will support the weight of the propellant partly by a shearing stress and only partly in direct tension. (This fact was first realised and incorporated into a motor design by G.W. Slack and C.G. Grant).

The question of the relative stresses near the endring and in the main part of the charge might be solved mathematically, but the most promising immediate attack on the problem is by the use of photoelastic models. Work on this is now in hand at E.R.D.E.

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4.2 Requirements for Temperature Cycling.

The propellant has a considerably higher coefficient of expansion than the tubing, the difference for plastic propellant amounting to some 3% by volume when integrated over the widest range of temperature required, 140°F. to -65°F. (+60°C. to -54°C.), and for colloidal propellants to some 5% by volume.

It is convenient to assume that the rocket tube is rigid, and that the bulk modulus of the propellant is infinite, so that the stresses involved are always sufficient to cause a change in shape of the charge exactly equivalent to the differential expansion involved. (In fact, on heating, the charge will tend to expand more than the tube and cause a hoop stress in the latter, and on cooling the reverse will happen. This stress in the tube could only be calculated if the bulk moduli etc. concerned were known. It is sufficient to say that plastic propellant has never yet been known to burst a tube on temperature cycling, but cordite has. It will probably be far easier to determine the transient and steady stresses in the tube by means of direct measurement with strain gauges, etc., than to try to calculate them after measuring bulk moduli, specific heats, thermal conductivities, the shear modulus of the propellant, etc. - all over a range of temperatures).

In the case of the first charge shape, cigar-burning, the expansion is constrained by the supporting pot so that all the change in volume is manifest as a change in contour of the free surface, as sketched in Figure 2(i). With good adhesion, the edge of the propellant surface cannot move, and the constraint is a maximum here and a minimum in the centre. For a Hookean elastic solid, the change in contour of the surface of the propellant will be a meniscus of a paraboloid, given by:

$$\frac{ds}{dT} = 2(1 - r^2/a^2). \frac{d(V_1-V_2)}{dT}/\pi a^2$$

On this basis, the angle of shear at any point on the surface is given by:

$$\theta = d/dr \int_{T_1}^{T_2} \frac{ds}{dT}$$

Taking the figure of 3% differential expansion previously quoted,

$$\int_{T_1}^{T_2} \frac{d(V_1-V_2)}{dT} / \ a^2 = 3\ l/100$$

Hence, $\theta = d/dr \ \{0.06\ l\ (1 - r^2/a^2)\}$

$= -0.12\ l\ r/a^2$

At the wall of the tube, $\theta_{max.} = -0.12\ l\,/a.$

In other words, for cycling between +60°C. and -54°C. without failure, the propellant must withstand repeated cyclic shearing through an angle of 0.12 l/a radians, that is, approximately 0.001 $l\Delta T/a$ radians, where ΔT is the temperature range in centigrade degrees.

If strain-hardening occurs, as with plastic propellant, this maximum angle is lessened, because the propellant near the motor wall gives a higher resistance to shear, and the extent of flow as a function of r is no longer parabolic.

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In practice P.I.B. plastic propellants have successfully withstood cycling between +60°C. and -40°C. for a number of cycles with a value of $1/a$ of 4.8, giving θ a value of about 0.5 radian.

In the case af a cigar-burning charge open at both ends, there is a plane of symmetry in the middle and for a given maximum angle of shear a double length can be used. This is subject to the proviso that gravitational stresses are not serious, i.e., that 'a' is small.

For charge shapes (ii) to (v) with internal conduits, temperature cycling causes little end flow, since there is comparatively free scope for lateral expansion into the gas conduit, with a longitudinal constraint, due to adhesion to the walls (and endrings, if present).

Subject to the above postulates, the change in area of the gas conduit is equal to:

$$\frac{d}{dT}\left(\frac{V_1 - V_2}{l}\right)$$

Typical figures for plastic propellants in steel are:

$$\frac{da}{dT} = \frac{dl}{dT} = 0.000011 \text{ per C}^{\circ}.$$

$$\frac{dV_2}{dT} = 0.003 \text{ to } 0.004 \text{ per C}^{\circ}. \text{ (average 0.0035)}$$

On this basis, the table below gives gas conduit volumes at different temperatures, expressed as a percentage of the value of V_1 at 60°C., for three loading densities.

	60°C. (140°F.)	0°C. (32°F.)	-54°C. (-65°F)
(i)	10.0	11.7	13.2
(ii)	30.0	31.5	32.8
(iii)	90.0	90.1	90.1

If (i) represents a cylindrical conduit, there will be a 15 per cent. change in its perimeter between 60°C. and -54°C. In the case of a star-shaped conduit, stress concentration occurs and the elongation perpendicular to the lines of maximum stress concentration might be increased by a factor of 2, 3 or so (no true figure is known). Clearly, the 'crack value' of the plastic or highly-elastic propellant must be at least, say, 40 per cent. to withstand such conditions, and the charge shape must be chosen so as to minimise stress-concentration. Furthermore, the propellant must not exhibit fatigue which would allow it to crack after several temperature cycles.

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A suggested basis for fatigue resistance is:

(a) A thousand temperature cycles between extreme day and night conditions in a dry continental climate, say 40°F. to 100°F., corresponding to ± 6 per cent. deformation at 20 - 25°C.

(b) A few - say twenty - cycles representing winter arctic blizzards, involving a fall of temperature from -15°F. to -65°F. corresponding to ± 5 per cent. deformation at -40°C., together with a 'brittle point' below -65°F.

(c) A very few cycles representing either aircraft flights from the tropics to the stratosphere, or else transits from a summer tropical to a winter arctic zone, corresponding to ± 20 per cent. deformation at 20 - 25°C.

There seems to be no reason why (c) might not be restricted to 5 or 10 cycles, followed by scrapping of the ammunition, if that solution were the only one available.

The change in size of the gas conduit is associated with a change in surface area of the propellant, proportional to the square root of the cross-sectional change for a simple cylinder, but to less than this in the case of a star-section. This is one reason why the ballistics of plastic propellants are less temperature-dependent than those of cordite rockets, where the surface area actually increases with temperature. In fact, the temperature coefficient with plastic propellant will vary a little with the charge shape. Conversely, however, if a rocket is designed to have a conduit not much larger than the venturi throat, the rate of gas flow over the plastic propellant is relatively enhanced by a rise in temperature. This necessitates a more strict limitation of gas velocities (that is port/conduit area ratios) in the case of plastic propellants, which is serious in the case of rapid-burning motors. There is a marked tendency to secondary pressure peaks under such conditions, which may well be accentuated by these considerations.

In addition to the stress concentration at re-entrant surfaces in the gas conduit, there is also a stress concentration at points where the surface of the propellant is stuck to metal. As indicated in previous paragraphs the calculation of actual stresses seems to be impossible. Again, however, the virtues of conical endrings, or the cone and cylinder charge shape, are evident.

Routine testing of plastic propellant is at present confined to temperatures of 25°C. and 60°C., and to a determination of 'brittle point', the latter being appreciably influenced by the rate of strain arbitrarily chosen. As first pointed out by Poole, in the case of failure on temperature cycling, the change in rheological properties in the ten degrees or so above the nominal brittle point is of paramount importance, and more work in this field is planned.

In order to study fatigue due to repeated temperature cycling, a plastometer has been made in which a pellet of plastic (or highly elastic) propellant is repeatedly compressed and stretched by a link mechanism driven from an eccentric operated by a geared-down electric motor. So far, measurements with this machine have been at room temperature. There is a correlation between the logarithm of the number of cycles to failure and the amplitude of movement, but much more work with different propellants at controlled

/temperatures

temperatures and slower rates of deformation is required before far-reaching conclusions on the ultimate serviceability of plastic propellants after exposure to severe cycling can be drawn. The development of P.I.B. propellants, which allow cycling over very much wider temperature ranges than heretofore, has, however, directed attention to fatigue failure of propellants on repeated cycling.

4.3 Rough Usage.

The currently-accepted test is a free drop of six feet on to strong concrete. The motor is accelerated at a rate 'g' over these six feet, and brought to rest in a distance given by the deformation in the concrete and metal member immediately in contact with it; it is then accelerated upwards again to an extent depending on the coefficient of restitution. The fact that heavy elastic metal objects do not bounce much is an indication that the majority of the energy is absorbed by the concrete, so presumably its deformation is, say, some five times that of the metal. A figure of a tenth of an inch for heavy objects seems reasonable, therefore; the acceleration is then of the order of 720 g applied for a time of about 1 millisecond. This imposes a maximum shear stress of about 320 a g ρ. For a five-inch motor this is about 60 p.s.i., and for a twenty four-inch motor about 300 p.s.i. It is not known what the limit is for plastic propellant, but five-inch and eight-inch motors will withstand several drops without adhesive or cohesive failure. The expense of this test, in man-hours needed to replace damaged metal components, etc., has precluded very extensive trials.

In 1948, some pellets of plastic propellant were fired from an airgun at a steel plate, mainly at -20°C., but the correlation of results with the brittle point of the propellant measured in other ways was poor, and the use of such a test as a means of controlling the effect of novel ingredients, etc., was not considered worth while. So far, apart from using binders of low brittle point, and salt grist specifications, wetting agent, etc., to give an acceptable crack value, there has been no systematic work to try to decrease the brittleness of plastic propellants to sudden severe impact, nor at present does there seem to be a need for such work, as there is with colloidal propellant.

4.4 Firing.

4.4.1 Hydrostatic Pressure.

The main effect of firing rocket motors is to subject the propellant to hydrostatic pressure. This is believed to have no effect on colloidal propellants, but there is contradictory evidence with plastic propellants. On the one hand, the results of the standard compression test appear to be independent of applied gas pressures (up to 1,000 p.s.i.) yet on the other hand the triaxial shear test (5) indicates that hydrostatic pressure causes a marked increase in the internal friction in the propellant, enabling it to support an excess compressive force in one direction, of up to half the hydrostatic pressure, for a relatively small deformation. Further work is in hand. Such an effect would enable the propellant to withstand much higher set-back forces than would be calculated from its properties under atmospheric pressure, but it is not allowed for in the following treatment. It may be pointed out that during a boost period the main motor of a missile is being accelerated in the absence of hydrostatic pressure.

Other important effects caused by firing the rocket are setback due to the inertia of the propellant against the acceleration, a steady pressure

/difference

difference between the head end and venturi end of the filling, and transient pressure differences due to ignition or secondary pressure peaks.

4.4.2 Dilation of Tube.

The hydrostatic gas pressure causes the rocket tube to dilate to an extent given by the hoop stress divided by the Young's modulus, that is aP/tE. It is convenient in practice, however, to relate the deformation directly to the elongation at the yield point of the metal divided by the factor of safety. This is unlikely to exceed $\frac{1}{2}$-1% for any metals now envisaged.

There will be a longitudinal strain equal to half the circumferential strain (P/tE times $\pi a^2/2\pi a$).

For propellants stuck to the rocket tube, as discussed before, the deformation at the surface of the gas conduit may rise to some 10-15% at lines of stress concentration, corresponding to $\frac{1}{2}$% linear expansion of the tube times ninefold density of loading factor times threefold stress-concentration factor. At low temperatures, this is superimposed on the deformation already present due to temperature cycling.

4.4.3 Effects of Air Inclusions.

The inclusion of air in plastic propellants (or any other solid propellant) can have disastrous effects. The 0.5% of dispersed air, which is the maximum amount allowed by the British plastic propellant density specification, can, on the above arguments, cause an additional deformation of up to 7% at lines of stress concentration. Before de-aeration was introduced, the air content was often 5-8% by volume. This could cause local deformations at the tips of the star-section conduit of some 100%. The effect of large individual air bubbles could be worse still. It is believed that many of the variable ballistic results obtained in early trials with plastic propellants were due to air inclusions. The effect would be greatly accentuated at lower temperatures (but temperatures normally reckoned considerably above the 'brittle point' of the propellant) due to the extremely high rate of deformation imposed on a very highly viscous and sluggish material, already deformed by differential expansion, causing rupture.

It must be emphasised that the assumptions made above are of the worst possible conditions. Stress-concentrations in a strain-hardening material are believed to be rarely threefold (measurements are conspicuous by their absence), and densities of loading as high as 90% have so far not come into regular use. Nevertheless, it is quite clear that the future is problematical for any propellant of low bulk modulus, due to air inclusions, fissures or any other cause, and that very careful consideration of stress concentration and the temperature cycling, etc., to be withstood, must be given to new motor designs which have very high densities of loading. Variants of simple cylindrical charge shapes have much to commend them, as regards stress concentration.

4.4.4 Setback Forces.

These have an effect similar to vertical storage, but the stress is multiplied by the acceleration (reckoned in terms of 'g') and the duration is only 1 to 40 seconds, or so. The 'flow test' results cease to be significant and the stabilisation due to strain-hardening of plastic propellants is no

/longer

longer sufficient to prevent flow. The limiting acceleration with which strain-hardening can cope is of the order of 60 g for 5-inch rockets and probably 10 g for very large rockets. Even this corresponds to a deformation that would be unacceptable in many charge shapes.

4.4.4.1 Plastic Flow.

There are two useful ways of considering the problem. For plastic propellants, the rate of flow is slow, due to the high viscosity. If we base the estimate of viscosity on the initial rate of deformation in the plasticity test at the highest temperature measured (60°C. or 140°F.), typical figures are 10^7 poises for P.I.B. propellants and 2×10^6 poises for dispolene propellants. In any case, the latter are unsuitable for full Service use, so the former figure will be used. It is, in fact, limited by the processing machinery at present available and the highest temperature of processing that can be used. If it were possible to work at 100°C. in place of 70°C., the 'viscosity' of the propellant would be much higher at 60°C., the highest likely temperature of usage. The viscosity will also undoubtedly depend on the rate of deformation, but no measurements on this effect have been made. The initial rate of deformation in the plasticity test would be relevant to normal rockets, but not to gun-launched motors.

For single-stage rockets with a very light warhead, the maximum overall S.I. is unlikely ever to exceed 150 sec., or for boosted rockets 250 sec. Hence, the integral of the acceleration over the time of burning could not exceed 250 g sec. or 8,000 feet/sec. in level flight. Practical velocities, with a normal payload and air resistance, are a quarter to a third of this. For present purposes, allowing a factor of safety, a final velocity of 4,000 feet/sec. is taken.

The average stress at the surface of an axial cylinder of radius r, in the propellant, is:

$$\pi r^2 l \rho f . F(r)/2 \pi r l = \tfrac{1}{2} \rho f r F(r)$$

In a cylindrical-conduit charge with a loading density of 90 per cent., $F(r)$ is zero for $r < a/\sqrt{10}$ and $F(r) = (r^2/a^2 - 0.10)$ for $r > a/\sqrt{10}$.

The gradient of rate of flow of the propellant, with respect to r, is: $dv/dr = (\text{stress} - \text{yield value})/\eta$

The effect of the yield value is to diminish $rF(r)$ by an amount depending on the deformation, but becoming constant for large deformations, and giving a correction of the order of 15 per cent. for a 2 foot diameter motor accelerated at 50 g. Neglecting this yield value:

$$dv = \rho f r F(r)\, dr/2\eta$$

Integrating over the period of the acceleration:

$$ds = \rho u r F(r) dr/2\eta$$

Integrating with respect to r, the overall flow of the inner surface is:

$$s = \frac{\rho u}{2\eta} \int_0^a r F(r) dr = \frac{\rho u}{2\eta} \int_{a/\sqrt{10}}^a (r^2/a^2 - 0.10) r\, dr$$

$$\therefore \quad s = 0.10 \rho u a^2/\eta$$

/Since

Since the contribution to this flow of the layers of propellant nearest the axis is small, a star-centred charge (with the same density of loading) would give nearly the same result.

If ρ = 1.8 gm./cc., u = 120,000 cm./sec. (4,000 feet/sec.), a = 30 cm. and η = 10^7 dynes/square cm./strob, the extent of flow would be 2.0 cm. This is about the limit likely to be acceptable for a conventional charge shape, since the venturi endring would divert the displaced material into the gas conduit (but would add to the local resistance against deformation so that the material actually displaced would be spread some few centrimetres up the conduit). In the case of a boosted sustainer motor, much of this flow would occur before actual ignition of the propellant, causing erosive conditions which might lead to excessive pressure. Similarly, at the head endring there would be a drop in web thickness which would lead to the exposure of metal before burning had finished.

Both these conditions could be overcome to some extent by the use of gently tapered conical or modified skirted endrings, and it might also pay to pare away some of the propellant for a distance of a few inches near the venturi end, as has been done experimentally with a star-centred 5-inch motor, without reducing the web thickness.

A more speculative method of minimising set-back, suggested independently by several people, would be to include a wire frame, or similar device, embedded in the propellant and fixed to the head end, so as to impose an added viscous drag.

Similar arguments apply to the case of a gun-launched rocket. The overall velocity will be no higher than that of a boosted rocket. In this case, however, there is a possibility of an appreciable transient elastic strain superimposed on the plastic flow of the propellant. No special measurements of elasticity of plastic propellant have yet been made. It can be deduced from the negligible elastic component of deformation in the normal plasticity test that the modulus of rigidity is certainly not less than 5 x 10^6 dynes/square cm.

To sum up, there is a very good prospect of being able to use P.I.B. plastic propellants in all rocket motors, including those boosted or gun-launched, up to a size limit of at least 2 feet in diameter. Individual charge designs which introduce new factors of size and acceleration will have to be examined more fully to confirm this. If the density of loading is reduced, the size limit is increased.

4.4.4.2 <u>Elastic Strain.</u>

For a highly-elastic propellant of negligible internal viscosity, set-back will cause an elastic deformation. For the internal-conduit charge shape previously considered, the main stress is a shear. The strain at the wall of the tube is 0.45 aρf/n, where n is the modulus of rigidity.

For large rockets, it has been stated that f will not exceed 50 g. Hence, for a 2 foot diameter motor, the strain at the wall of the tube, calculated as above, is 1.21 x 10^6/n radians. Integrating over the web thickness, the linear setback at the inner surface of the propellant could be as high as 8 x 10^6/n cm. (The severest possible conditions have again been postulated). The modulus of rigidity of a typical soft natural rubber is about 3 or 4 x 10^6 dynes/square cm./radian. This would give about 2 cm. deformation, as for a plastic propellant.

/Any

Any viscous resistance of rubbery materials has been neglected. This is considered to be quite valid, and simply implies that the modulus should be measured in the laboratory under much the same rate of loading as is encountered in use. In fact, the molecular rearrangement associated with high elasticity is normally the internal straightening of molecules, which can usually occur without the need for macroscopic viscous flow between various molecules.

The case of a gun-launched rocket filled with a high-elastic propellant forms an interesting contrast with plastic propellants; the deformation is proportional to the acceleration, whereas with the plastic propellant it is independent of the acceleration. Hence, under high accelerations, plastic propellant will behave better than elastic (assuming its cohesive strength is not exceeded by the applied acceleration stresses).

The linear setback of elastic propellant is proportional to the square of the web thickness and the maximum angular strain directly to the web thickness. Hence the maximum permissible acceleration will be inversely proportional to the diameter of the rocket, or to the square of the diameter, depending on whether the propellant ruptures before reaching its highest acceptable deformation. A figure for soft rubber in a 3-inch motor would be of the order of 500 g. A rigorous examination of such a system would be complicated by pulses of deformation being reflected at endrings, etc., since the speed of transmission of longitudinal vibrations in rubber is relatively low.

4.4.5 Pressure Gradients.

4.4.5.1 It is possible that the pressure at the head end of a rocket could exceed that at the venturi end by as much as 200 p.s.i., maintained during the first part of burning, in the case of a motor with a gas conduit small compared with the venturi throat. This would tend to displace the propellant towards the venturi. Neglecting the variable contribution of erosive burning, the usual gas-dynamic relationship approximates to the condition that the pressure drop (on a logarithmic scale) is a function of the square of the gas velocity. The gas velocity will be zero at the head end and will increase rather more rapidly than linearly down the charge (due to the slight drop in density and the contribution of erosive burning). The pressure gradient will therefore be very low at the head end and will increase steadily towards the venturi end; it might reach 10 p.s.i./inch towards the venturi end. It could be greatly reduced, if required, by tapering the conduit in the way mentioned above to overcome the effect of setback.

The shearing stress corresponding to a pressure gradient of 10 p.s.i. per linear inch, assuming that it is transmitted freely as a hydrostatic pressure within the charge (the worst possible condition), is 280,000 dynes/square cm./cm. This will cause a steady flow in a plastic propellant, or a strain in an elastic propellant.

4.4.5.2 The rate of flow at the conduit surface of a plastic propellant of viscosity 10^7 poises will be 280,000 w/10^7 cm/sec., where 'w' is the web thickness.

In a 2 foot diameter motor, 'w' will not exceed 6 inches (15 cm.), so the extent of flow in 1 second might attain 4 mm.

4.4.5.3 The strain in a corresponding soft elastic propellant (if n = 4 x 10^6 dynes/square cm.) would be 1 cm. One second is a reasonable time

/to

to assume, since the conditions of high pressure gradients very rapidly subside as the gas conduit burns to a larger diameter.

It may be concluded that the maximum permissible sustained pressure gradient in large rockets is of the order of 10 p.s.i./inch.

4.4.6 Igniter Peak Pressures.

These are much more transient than those considered above, so that they can be ignored in the case of bodily flow of highly viscous plastic propellants. However, there is a possibility that the 'viscosity' may fall off at very rapid rates of shear, that is under high stresses, due to elasticity. There is a further possibility that the 'crack value' as normally measured, in a time of the order of a few seconds, does not truly represent the crack value under shock loading. Further work on these problems is required.

For elastic propellants, in the same way, the physical properties at very high rates of loading are required. There is a chance of setting up severe longitudinal waves unless the degree of internal damping is high. Actual conditions in a rocket might be studied by X-ray flash photography, but an exploration in terms of direct laboratory measurements of the physical properties concerned is always valuable.

Secondary pressure (resonance) peaks are not well enough studied to predict their effects. Judging from some burnt-out experimental plastic propellant motors, resonance can cause rhythmic variations in propellant thickness of several millimetres. The propellant in question, at ambient temperatures, had a 'viscosity' of only 5×10^6 poises, dropping to 1×10^6 ar 60°C. It is hoped that the use of much more viscous compositions will render this trouble negligible.

4.4.7 Rotation and Guidance.

If a plastic or elastic propellant rocket is rotated about its own axis the main centrifugal force is taken by the walls of the tube, and there will simply be a hydrostatic pressure in the filling. Where the filling is not continuous with the container, at the ends of a charge where there are no endrings, or in the flutes of a star-centred charge, unbalanced stresses will occur, tending to force the propellant outwards.

Conditions at a point in any cylindrical shell of elastic filling will be the same as in a direct compression test, where the stress is that due to the hydrostatic pressure generated by the column of propellant between the point considered and the axis of the tube, that is:

$$\int \rho\, w^2 r.\,dr \qquad \text{dynes/square cm.}$$

where w is the angular velocity in strobs and the integral is confined to the space actually occupied by propellant.

For a 2 ft. diameter charge, with 90% density of loading, with propellant of density 1.8 gm/cc., rotating at 1 rev/sec., the average wall pressure is approximately:

$$7.2\,\pi^2 \int_{9.3}^{30} r.\,dr. = 29{,}000 \text{ dynes/square cm.}$$

/This

This pressure would cause only 0.3% compression in soft rubber ($Y.M. = 10^7$ dynes/square cm) and a very slow rate of flow in P.I.B. plastic propellant, a decrease in web thickness of some 0.3%/sec., falling to zero on strain hardening.

The deformation acceptable in a motor depends very much on motor design; a round figure might be ten times that given above. Again, for small rotated motors filled with plastic propellant, the time of burning would be very short, allowing a design giving a higher rate of flow than in larger motors. Special calculations should be made in every individual case. Rapid rotation (spin-stabilisation) would appear to be permissible only with well supported charges.

If the rocket is rotated off axis, the part of the filling nearest to the axis is subjected to a tensile stress. P.I.B. plastic propellant will elongate unacceptably fast if this stress exceeds about 3 p.s.i.; highly-elastic materials will stand far more than this, but the shape of the charge will be deformed appreciably at 20 p.s.i., assuming the modulus of rigidity is 3 or 4×10^6 dynes/square cm. If the distance off axis is 'x' feet and the web thickness 'w' inches, it follows that P.I.B. plastic propellant will stand about $400/\sqrt{xw}$ r.p.m. and soft rubbery propellants some $1000/\sqrt{xw}$ r.p.m.

If the path of a rocket is altered, the permissible sideways acceleration is, correspondingly, about 45 g/w for P.I.B. propellants and 300 g/w for soft rubbery propellants. However, in general, the rocket will be partly burned at this stage of its flight, and 'w' will be less than its original value. Accelerations up to 10 g should be tolerated by both types of propellant, taking w as $4\frac{1}{2}$ inches.

In each of the last cases, the overall flow of plastic propellant for a sustained stress would require evaluation.

5. DISCUSSION.

The main theme of this paper is to obtain an insight of the limitations of propellants for large rocket motors.

It has been demonstrated that the theoretical limit for present plastic propellants in motors with a high density of loading is of the order of at least 2 feet in diameter. As rockets approach this size, the specification of the propellant will have to be critically reviewed to ensure that the minimum 'viscosity' is maintained and the 'crack value' is not too low. The 'crack value' test may have to be extended to include rapid single loading and repeated slow cycling. Specifications for cohesive and adhesive strength may have to be introduced with both very long and very short times of loading. Finally, there will probably be a larger range of motor sizes, perhaps up to some 6 feet in diameter, where the usage of the propellant will need to be limited to a low density of loading or to certain rather low temperatures, unless more robust processing machinery or higher processing temperatures can be adopted, with corresponding increases in 'viscosity' and cohesive strength of the propellant.

It has been shown that the limitations of plastic propellants are more and more serious as the size of motor increases, as the 'viscosity' falls, and, particularly, as the 'density of loading' and degree of stress concentration in the motor rise. There is a practical limit to density of loading of axial conduit charges, related to the range of temperature cycling, which is of the order of 85 per cent. by volume for the widest temperature ranges, rising to perhaps 90 per cent. in the case of a motor with a cylindrical conduit. There is a limit to the length/diameter ratio of cigar-burning charges, again related to the temperature range.

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In the case of highly elastic propellants, it has been shewn that the modulus of rigidity of a soft rubber (some 4×10^6 dynes/square cm.) would again limit charges to some 2 feet in diameter for low accelerations, and to very much smaller sizes for high accelerations. The desirable shear modulus for a highly-elastic propellant would be at least 10^7 dynes/square cm.

As for plastic propellants, the 'crack value' (related to the elongation at break) must be high, say 40 per cent., for both rapid single stressing and for slow repeated stressing (implying fatigue resistance).

The nature of the 'highly elastic propellant' has deliberately been ignored in the main part of the paper; it is immaterial to the considerations reviewed there. There are numerous possibilities. A soft cordite (e.g. Mark I), especially if reinforced with carbon black, has a sufficiently high elongation and modulus of rigidity. However, it would become too brittle around -20°C. and under high stresses it undergoes 'cold flow'. Possibly it could be slightly cross-linked in a reproducible manner, and without giving N.G. exudation; or again, as with some synthetic rubbers, reinforcement by very fine fillers would help.

Possibly an oxygenated monomer will be developed which could polymerise to a rubber, perhaps with suitable plasticisation by a liquid nitric ester. Failing these 'colloidal' rubbery propellants, a 'composite' propellant, employing an inorganic salt as oxidant, might be used. There is already the American "thiokol" propellant, and depolymerised rubber (natural or butyl) has been tried on a small scale by E.R.D.E.; further laboratory work is in hand, mainly to elucidate such problems as wetting of the filler.

There is, however, another possibility, proposed by Poole. That is to have a normal colloidal propellant charge split up into segments each bedded in an inert rubbery material, free to expand and contract at the junctions between the segments. This is also being tested on a small scale. Its advantages are mainly, at first sight, associated with the possibility of easier manufacture and inspection, coupled with protection of the cordite from brittle fracture at low temperatures. A variant of this idea, suitable for many motor designs, would be to use a highly-elastic material to inhibit colloidal propellants; some work on these lines has already been done (6). If this material combined a reasonably high modulus of rigidity, good tear-resistance, etc., with a porous or ribbed structure, so that it could accomodate volume changes on temperature cycling and yet always be a tight fit in the motor tube, it might be a good competitor to the plastic or liquid surround of the "Demon" motor, and eliminate all difficulties associated with supporting colloidal propellant charges on a grid, or its equivalent.
It is thought that these considerations amply justify some work on highly-elastic inhibitors, especially in view of supply difficulties with ethyl cellulose.

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7. ACKNOWLEDGMENTS.

The work referred to in this Technical Note has been largely carried out by or under the direction of Mr. P.R. Freeman, who has done much to improve the mechanical properties of plastic propellants. Helpful discussions have also been held with many members of E.R.D.E., R.A.E./R.P.D., A.D.E. and A.R.E.

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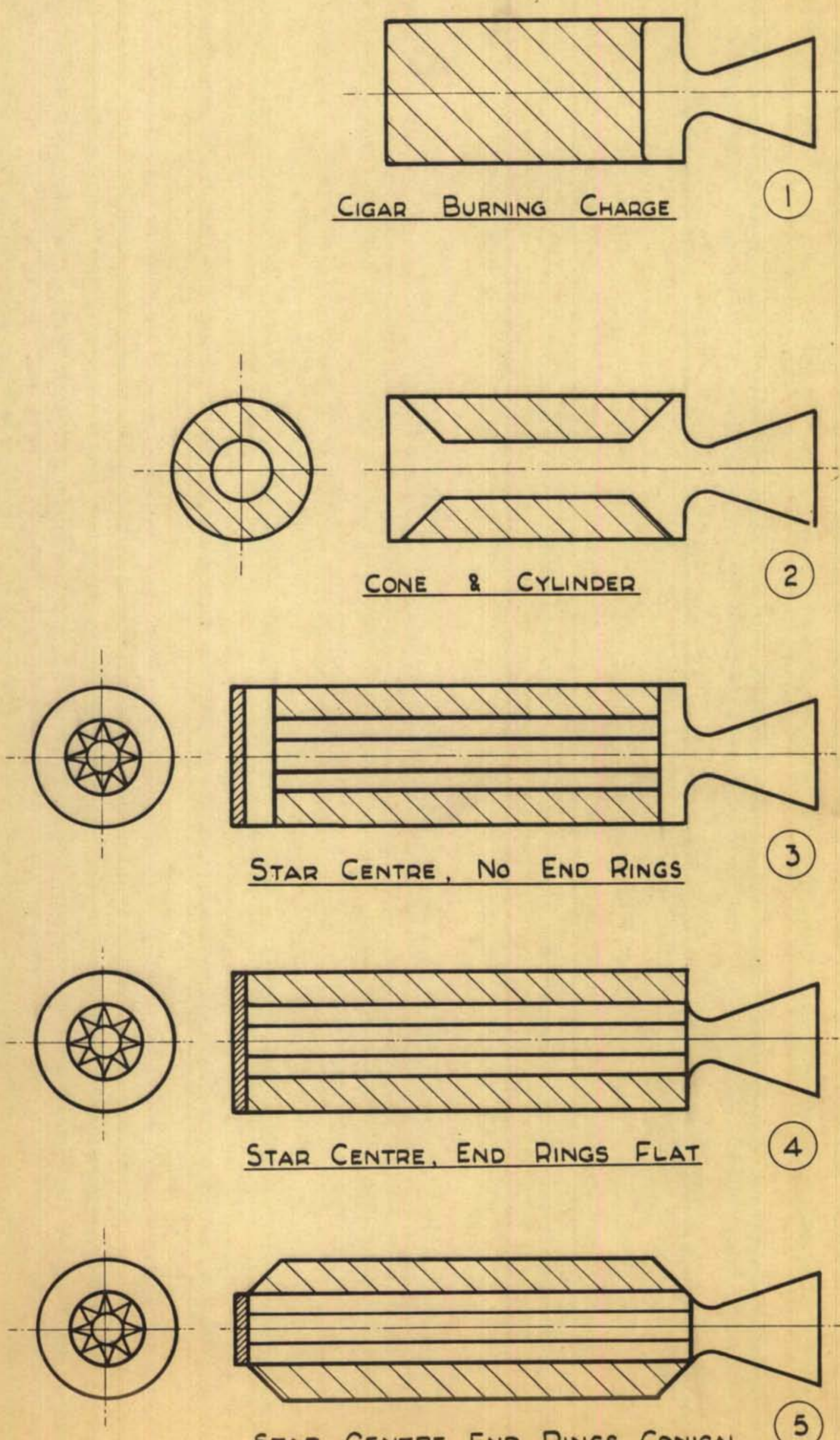

AXIAL SECTIONS & END VIEWS OF ROCKET CHARGES

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FIG. 1

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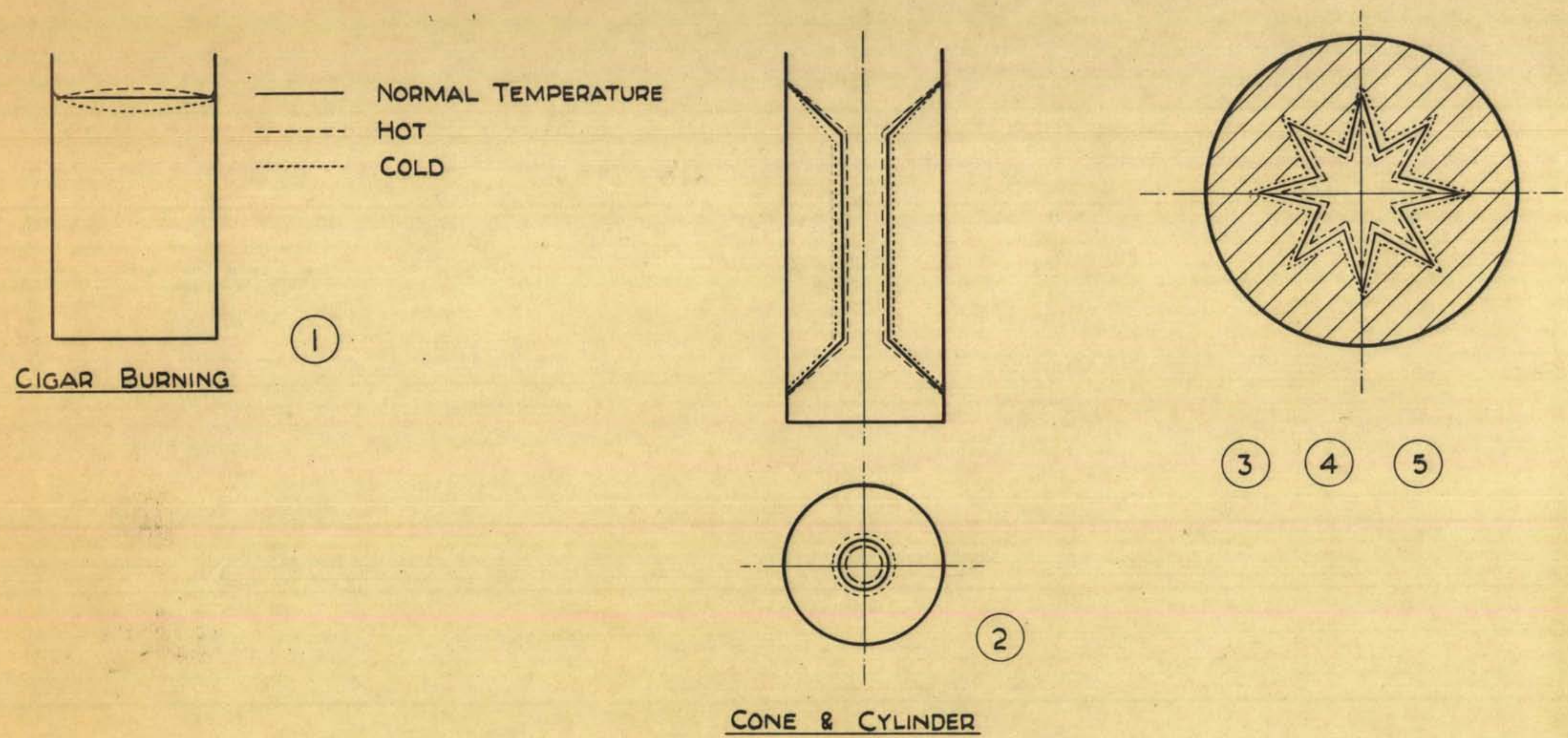

CHANGE IN CHARGE SHAPES DUE TO TEMPERATURE CYCLING

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FIG. 2